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How do migratory species stay healthy over the annual cycle?

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Supplementary Tables

This material consists of a review of literature pertaining to measures of immune function, pathogen pressure and disease resistance. This review was used, in combination with the work synthesized in the main article, to develop the ideas presented in the conceptual model. We acknowledge that this review is not exhaustive, but we feel that it is a useful to identify patterns and inconsistencies in the literature. Table 1 gives a list of abbreviations used, Table 2 summarise relationships between immune function and survival, disease, migration, reproduction, molt, energy balance, and genetics; in correlative and experimental studies; at the individual and population levels. Table 3 gives details of all studies in alphabetical order.

Notes on Table S2

Immune function and survival

- It is important to remember that a correlation between immune function and survival is not directly indicative of disease resistance. Both survival and the immune function are linked to condition. Animals in poorer condition may have increased disease susceptibility, but may also be less able to find food or avoid predators.

Immune function and disease

- Correlative studies may be more indicative of current infection (which can be interesting in itself) than immunocompromise or immunocompetence.
- Experimental studies are needed to prove disease resistance.
- Constitutive immunity seems to be positively correlated with current infection while PHA induced wind web swelling seems to be hindered by it (likely because this measure is condition dependent).
- Current infection does not seem to affect specific antibodies to novel antigens (although obviously antibodies to the pathogen currently infecting the individual are expected to be high).

- Specific antibodies seem to be positively correlated with disease at population level, which may indicate high exposure of whole population to multiple pathogens.
- The experimental selection experiment (Gross et al. 1980) highlights the fact that different pathogen types are eradicated by different aspects of immune function. This also highlights the importance of placing results in the context of pathogen pressure, since competence against one pathogen may mean susceptibility to another.

Immune function and reproduction

* Refers to correlative studies of naturally reproducing birds in the wild or studies where reproduction was induced in captivity but reproductive effort was not manipulated.

- PHA induced wing web swelling is generally negatively related to reproduction. The exception is a study looking at various passerine species in the wild which found PHA induced wing web swelling to be positively correlated with reproduction (breeding versus non-breeding season; (Møller et al. 2003). However, this may be due to differences in pathogen pressure between breeding (summer) versus non-breeding (winter); an idea that is supported by higher PHA responses in cavity versus cup nesting species.

Immune function and molt

- PHA induced wind web swelling as well as phagocytosis and inflammation based aspects of constitutive immune function are negatively correlated with molt in captive birds (Buehler et al. 2008; Martin 2005).

Immune function and reproductive effort

* Refers to studies where reproductive effort was manipulated.

- Constitutive immunity is positively correlated with reproductive effort (Ilmonen et al. 2003). This may be due to stress and/or higher levels of current infection during reproduction. It cannot be because better quality birds have both better

reproduction and better immune function since reproductive effort was manipulated.

Immune function and genetics

- Genomic diversity (as measured by microsatellites) and specific MHC alleles (but not diversity of alleles) appear positively linked to induced acquired immunity
- Little is known about genes related to constitutive immune function, induced innate immune function or immune response regulation in non-model species.

Disease and genetics

- Genomic diversity (as measured by microsatellites) appears to be negatively correlated with disease.
- Specific MHC alleles can confer resistance or susceptibility depending on the allele or the population in question. If multiple diseases were studied it would likely depend on the type of pathogen as well.

Table S1: Abbreviations used in Tables 2 and 3

Aspects of Immune Function	
CA	Constitutive acquired immunity (linked to specific recognition; i.e. lymphocytes, macrophages and baseline antibody levels)
CI	Constitutive innate immunity (non-specific recognition; i.e. granulocyte phagocytosis, baseline complement)
IA Th1	Induced acquired immunity (induced responses employing Type 1 helper T-cells and cell-mediated components using specific recognition of pathogens)
IA Th2	Induced acquired immunity (induced response employing Type 2 helper T-cells and humoral components using specific recognition of pathogens)
II	Induced innate immunity (non-specific induced response; i.e.acute phase response, inflammation)
Immune assays	
APR	acute phase response
H	heterophil count
H:L	heterophil to lymphocyte ratio
HL-HA	hemolysis-hemagglutination assay
Hp	haptoglobin assay
IgG	baseline levels of serum IgG
KLH	keyhole limpet haemocyanin injection to induce specific antibodies
L	lymphocyte count
LPS	lipopolysaccaride to induce acute phase response
Microsat H	microsatellite heterozygousity
MK	microbial killing
MHC	major histocompatibility complex
P	phagocyte count
PA	phagocytosis assay
PHA	phytohaemagglutinin to induce wing web swelling
SRBC	sheep red blood cells injected to induce specific antibodies
T-D	tetanus-diphtheria vaccine injected to induce specific antibodies
WBC	total leukocyte count

Table S2: A summary of the relationships between immune function and survival, disease, migration, reproduction, molt, energy balance, and genetics

INDIVIDUAL LEVEL CORRELATIVE				
	Positive	**Negative**	**No association**	**Study**
Immune function and survival	IA Th1 (PHA) & 3 month survival	IA Th2 (SRBC) & 3 month survival		Gonzalez et al. 1999
	IA Th1 (PHA) & 1 to 2 year survival			Soler et al. 1999
	IA Th2 (SRBC) & 3 year survival			Ardia et al. 2003
	CA (L) & 1 year survival		CI (WBC) & 1 year survival	Kilgas et al. 2006
Immune function and disease		IA Th1 (PHA)	IA Th2 (SRBC)	Gonzalez et al. 1999
	CI/CA (WBC)			Apanius et al. 2000
		IA Th1 (PHA)		Navarro et al. 2003
	CI/CA (WBC)			Davis et al. 2004
Immune function and migration		CI/CA (L, WBC)		Owen and Moore 2006
	CI/CA (WBC, MK *S. aureus*)		CI (MK *E. coli*, HL-HA)	Buehler et al. 2008
Immune function and reproduction*	IA Th2 (cytokines)	IA Th1 (cytokines)		Wegmann et al. 1993
	IA Th1 (PHA)			Møller et al. 2003
		II APR (LPS)		Owen-Ashley and Wingfield 2006
Immune function and molt	CA (L, WBC)	CI (H, MK *S. aureus*)	CI (MK *E. coli*, HL-HA)	Buehler et al. 2008
Immune function and condition	IA Th1 (PHA)		IA Th2 (SRBC)	Gonzalez et al. 1999
	IA Th1 (PHA)			Ilmonen et al. 2003
	IA Th1 (PHA)			Navarro et al. 2003
	CA (L); IA Th1 (PHA)		CI (P); CA (IgG)	Owen and Moore 2008a
Immune function and energy	IA Th1 (PHA) & temperature, food			Lifjeld et al. 2002
	IA Th2 (cytokines) & over training	IA Th1 (cytokines) & over training		Smith 2003

Table S2 (continued):

INDIVIDUAL LEVEL CORRELATIVE continued				
	Positive	**Negative**	**No association**	**Study**
Immune function and genetics	Microsat H & IA Th1 (PHA)			Hawley et al. 2005
	specific MHC alleles & IA Th1 (PHA) Th2 (SRBC)		total # MHC alleles and IA Th1 (PHA)	Bonneaud et al. 2005
			total # MHC alleles and IA Th1 (PHA)	Hale et al. 2009
Disease and genetics		Microsat H		Hawley et al. 2005
		Microsat H		MacDougall-Shackleton et al. 2005
	specific MHC alleles	specific MHC alleles		Bonneaud et al. 2006
		Microsat H		Ortego et al 2007
	specific MHC alleles	specific MHC alleles		Barribeau et al. 2008
		Microsat H (in genes)	Microsat H (neutral)	Luikart et al. 2008
	specific MHC alleles	specific MHC alleles		Kloch et al. 2010

* Studies of naturally reproducing birds in the wild or studies where reproduction was induced in captivity but reproductive effort was not manipulated.

Table S2 (continued):

INDIVIDUAL LEVEL EXPERIMENTAL				
	Positive	**Negative**	**No association**	**Study**
Immune function and survival		II APR (LPS) with starvation & 30 hour survival		Moret and Schmid-Hempel 2000
Immune function and disease			IA Th1 (PHA), IA Th2 (SRBC)	Hawley et al. 2007
Immune function and migration		IA Th1 (PHA)		Owen and Moore 2008b
Immune function and reproduction	IA Th1 (PHA) courtship	IA Th1 (PHA) chick rearing		Martin et al. 2004
		IA Th1 (PHA)		Greenman et al. 2005
Immune function and molt		IA Th1 (PHA)		Martin 2005
Immune function and reproductive effort**		IA Th2 (SRBC) & brood size (parent)		Ardia et al. 2003
	CI/CA (WBC) & brood size (parent)	IA Th1 (PHA) & brood size (nestlings)	IA Th2 (T-D) & brood size (parent)	Ilmonen et al. 2003
Immune function and energy	IA Th1 (PHA) & diet	IA Th2 (SRBC) & diet		Gonzalez et al. 1999
			IA Th1 (PHA), CI (WBC) & workload	Soler et al. 1999
	IA Th1 (PHA) & food			Alonso-Alvarez et al. 2001
	IA Th1 (PHA) & metabolic rate			Martin et al. 2003
			IA Th1 (PHA), Th2 (T-D) & workload	Hasselquist et al. 2007
			CI/CA (WBC, MK, HL-HA) & temperature	Buehler et al. 2008
			CI (PA, MK, WBC) & workload	Tieleman et al. 2008
		II APR (LPS) & food access	CI/CA (WBC, MK, HL-HA, Hp) & food access	Buehler et al. 2009

** Refers to studies where reproductive effort was manipulated.

Table S2 continued:

POPULATION LEVEL CORRELATIVE				
	Positive	**Negative**	**No association**	**Study**
Immune function and disease	IA Th2 (KLH); CA (IgG)	IA Th1 (PHA)		Lindström et al. 2004
Immune function and reproduction	IA Th1 (PHA) difference greatest in hole nesters			Møller et al. 2003
	IA Th1 (PHA) early breeding season for temperate birds	IA Th1 (PHA) late breeding season or temperate birds	IA Th1 (PHA) tropical birds	Martin et al. 2004
Disease and genetics	specific MHC alleles depending on population	specific MHC alleles depending on population		Bonneaud et al. 2006
	specific MHC alleles depending on population	specific MHC alleles depending on population		Kloch et al. 2010

POPULATION LEVEL EXPERIMENTAL				
	Positive	**Negative**	**No association**	**Study**
Immune function and disease (selection experiment)	IA Th2 (SRBC) & *M. gallisepticum* (fungus like bacteria), *E. necatrix* (protist), a splenomeglia virus, and feather mites	IA Th2 (SRBC) & *E. coli* (gram-negative bacteria) and *S. aureus* (gram-postitive bacteria)		Gross et al. 1980

Table S3: Details of the studies presented in Table S2

Study	Species	System	Disease	Conditon	Energy Balance	Genes	Immune assays	Immune aspect
Alonso-Alvarez et al. 2001	Yellow-legged gulls (*Larus cachinnans*)	captive, experimental, individual level			restricted food		PHA	IA Th1
Apanius et al. 2000	various tropical Passerine species	free-living, correlative, individual level	Avian malaria *Haemoproteus*				WBC	CI
Ardia et al. 2003	Tree swallow (*Tachycineta bicolor*)	free-living, experimental, individual level			brood size		SRBC	IA Th2
Barribeau et al. 2008	Frogs (*Xenopus laevis*)	captive, experimental, individual level	Bacteria *Aeromonas hydrophila*			MHC alleles		
Bonneaud et al. 2005	House sparrows (*Passer domesticus*)	captive, experimental, individual level				MHC alleles	PHA and SRBC	IA Th1 and Th2
Bonneaud et al. 2006	House sparrows (*Passer domesticus*)	free-living, correlative, individual and population level	Avian malaria *Plasmodium* and *Haemoproteus*			MHC alleles		
Buehler et al. 2008	Red knots (*Calidris canutus*)	captive, experimental, individual level			temperature and annual cycle		WBC, MK (*E. coli, S. aureus*), HL-HA	CI and CA

Table S3 continued:

Study	Species	System	Disease	Conditon	Energy	Genes	Immune assays	Immune aspect
Buehler et al. 2009	Red knots (*Calidris canutus*)	captive, experimental, individual level			access to food		WBC, MK (*E. coli, S. aureus*), HL-HA, Hp, APR (LPS)	CI, CA, II
Davis et al. 2004	House Finches (*Carpodacus mexicanus*)	free-living, correlative, individual level	conjunctivitis, *Mycoplasma gallisepticum*				WBC	CI
Gonzalez et al. 1999	House sparrows (*Passer domesticus*)	captive, experimental, individual level	Avian malaria *Haemoproteus*	body mass	protein rich or protein poor diet		PHA and SRBC	IA Th1 and Th2
Greenman et al. 2005	House sparrows (*Passer domesticus*)	captive, experimental, individual level			annual cycle		PHA	IA Th1
Gross et al. 1980	Chicken (*Gallus gallus*)	captive, selection experiment, population level	*M. gallisepticum*, *Eimeria necatrix*, splenomeglia virus, feather mites, *E. coli, S. aureus*				selected for high antibody response to SRBC	IA Th2
Hale et al. 2009	Peafowl (*Pavo cristatus*)	captive, correlative, individual level				MHC alleles	PHA	IA Th1
Hasselquist et al. 2007	Red knots (*Calidris canutus*)	captive, experimental, individual level			flight in a wind tunnel		PHA and T-D	IA Th1 and Th2

Table S3 continued:

Study	Species	System	Disease	Conditon	Energy	Genes	Immune assays	Immune aspect
Hawley et al. 2005	House finch (*Carpodacus mexicanus*)	captive, experimental, individual level	*M. gallisepticum* (conjunctivitis)			Microsat H at 12 loci	PHA	IA Th1
Hawley et al. 2007	House Finches (*Carpodacus mexicanus*)	captive, experimental, individual level	*M. gallisepticum* (conjunctivitis)				PHA and SRBC	IA Th1 and Th2
Ilmonen et al. 2003	Pied flycatchers (*Ficedula hypoleuca*)	free-living, experimental, individual level		H:L ratio	brood size		WBC, PHA and T-D	CI, CA, IA Th1 and Th2
Kilgas et al. 2006	Great tits (*Parus major*)	free-living, correlative, individual level		H:L ratio			WBC	CI and CA
Kloch et al. 2010	Bank vole (*Myodes glareolus*)	free-living, correlative, individual and population level	Intestinal nematodes, *Aspicularis tetraptera, Heligmosomum mixtum* and *Heligmosomoides glareoli*			MHC alleles		
Lifjeld et al. 2002	Tree swallow (*Tachycineta bicolor*)	free-living, correlative, individual level			cold weather, food abundance		PHA	IA Th1

Table S3 continued:

Study	Species	System	Disease	Conditon	Energy	Genes	Immune assays	Immune aspect
Lindström et al. 2004	Ground finches (*Geospiza fuliginosa*)	free-living, correlative, island/population level	ectoparasites *Trouessartia* and *Proctophyllodes*	body mass			IgG, PHA and KLH	CA, IA Th1 and Th2
Luikart et al. 2008	Bighorn sheep (*Ovis canadensis*)	free-living, correlative, individual level	lungworm *Protostrongylus*			Microsat H at 15 loci		
MacDougall-Shackleton et al. 2005	Mountain white-crowned sparrows (*Zonotrichia leucophrys oriantha*)	free-living, correlative, individual level				Microsat H and genetic diversity at 7 loci		
Martin 2004	House sparrows (*Passer domesticus*), tropical and temperate	captive, experimental, individual and population level			annual cycle		PHA	IA Th1
Martin 2005	House sparrows (*Passer domesticus*)	captive, experimental, individual level			molt		PHA	IA Th1
Martin et al. 2003	House sparrows (*Passer domesticus*)	captive, experimental, individual level			resting metabolic rate (RMR)		PHA	IA Th1
Møller et al. 2003	various temperate Passerine species, hole and cup nesters	free-living, correlative, individual and guild level			breeding vs. non-breeding		PHA	IA Th1

Table S3 continued:

Study	Species	System	Disease	Conditon	Energy	Genes	Immune assays	Immune aspect
Moret and Schmid-Hempel 2000	Bumblebee (*Bombus terrestris*)	captive, experimental (starvation and immune challenge), individual level					APR (LPS)	II
Navarro et al. 2003	House sparrows (*Passer domesticus*)	free-living, correlative, individual level	Avian malaria *Haemoproteus*	body mass			PHA	IA Th1
Ortego et al. 2007	Lesser kestrel (*Falco naumanni*)	free-living, correlative, individual level	feather lice *Degeeriella rufa*			Microsat H at 11 loci		
Owen and Moore 2006	Thrushes (*Hylocichla mustelina, Catharus* sp)	free-living, correlative, individual level					WBC, IgG	CI and CA
Owen and Moore 2008a	Thrushes (*Hylocichla mustelina, Catharus* sp)	free-living, correlative, individual level		fat, muscle, condition index, H:L ratio			WBC, IgG and PHA	CI, CA and IA Th1
Owen and Moore 2008b	Swainson's thrush (*Catharus ustulatus*)	captive, experimental, individual level		migratory restlessness			PHA	IA Th1

Table S3 continued:

Study	Species	System	Disease	Conditon	Energy	Genes	Immune assays	Immune aspect
Owen-Ashley and Wingfield 2006	Song sparrow (*Melospiza melodia morphna*), males	free-living, correlative, individual level		breeding vs non-breeding			APR (LPS)	II
Smith 2003	Humans (*Homo sapiens*)	free-living, correlative, individual level			exercise (over training)		Cytokines for Th1 and Th2 responses	IA Th1 and Th2
Soler et al. 1999	Black wheatears (*Oenanthe leucura*)	free-living, experimental (workload), correlative (disease), individual level	*Mallophaga* feather lice and *Hematophagous* mites	hematocrit	flight costs (wing clip)		WBC and PHA	CI, CA and IA Th1
Tieleman et al. 2008	House wrens (*Troglodytes aedon*)	free-living, experimental, individual level			flight costs (wing clip)		WBC, MK (*E. coli*), PA (*E. coli, S. aureus*)	CI and CA
Wegmann et al. 1993	Humans (*Homo sapiens*)	free-living, correlative, individual level			pregnancy		Cytokines for Th1 and Th2 responses	IA Th1 and Th2

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